Warm and Hot Diffuse Gas in Dwarf Galaxies

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Abstract

Dwarf galaxies provide a special environment due to their low mass, small size and generally low metal content. These attributes make them perfect laboratories for the interaction of massive stars with the interstellar medium on small and especially large spatial scales. The natural result of the spatially concentrated energy output from stellar winds and supernovae of an OB association is an expanding bubble. These bubbles can grow to kpc-size and become the dominant driver of the chemical and dynamical evolution of dwarf galaxies. In such low mass systems, bubbles have an enhanced probability of breaking out of the gaseous disk into the halo of the host galaxy. This may lead to venting metal enriched hot gas to large distances from the sites of creation. In this work I review the current observational material on hot gas inside bubbles, blow-outs, and hot halos of dwarf galaxies and discuss several conclusions which can be drawn from the observations. I will also present an analysis of the dwarf galaxy NGC 1705 as a case study, highlighting observational methods and problems with the current data. Finally I will comment on some areas where large progress should be possible in the near future.

1 Introduction

Dwarf galaxies, by definition of their class, are galaxies of low mass and size. This directly implies that they have a much weaker gravitational potential well than typical spiral galaxies and fill a smaller volume with gas and stars. All dwarf galaxies, even very low mass systems, show quite complicated star formation histories (e.g. Mateo 1998). From the color-magnitude diagrams one derives the presence of some low level star formation activity over most of the lifetime, sometimes interrupted by short intervals of strongly enhanced star formation rate. These results and the presence of blue compact dwarf galaxies, where the current star formation rate is so high that these dwarf galaxies appear as isolated giant HII regions, tells us that bursts of star formation are indeed a natural process in dwarf galaxies, as predicted by models of stochastic self propagating star formation (Gerola et al. 1980). Bursts of star formation, meaning spatially and temporally correlated energy input

from massive stars and supernova explosions inside physically small systems, lead to a strong response of the gas in the host galaxy.

Analytical and numerical modeling of the reaction of the gas to the energy input from stellar winds and supernovae is an active topic since the papers of Castor et al. (1975) and Weaver et al. (1977). Recent examples are e.g. Freyer & Hensler (2000), Strickland & Stevens (2000), Mac Low & Ferrara (1999), and Tomisaka (1998). For a review of the basic ideas, see Tenorio-Tagle & Bodenheimer (1988). The result of the energy input into the interstellar medium (ISM) is basically an expanding bubble of hot gas inside the substrate of cool gas of the host galaxy. The hot bubble is enclosed by a dense cool shell, which has ionized gas at the inner boundary layer between the hot gas and the shell. If the bubble grows to a linear diameter comparable to the neutral gas scale height of the galaxy, the expansion speeds along the z-axis (e.g. Mac Low & McCray 1988) and the shell expands into the lower halo of the host galaxy while starting to deform and break due to Rayleigh-Taylor instabilities (e.g. Mac Low et al. 1989).

Since massive stars and supernova explosions are the dominant source of heavy elements, the newly processed material is located inside the shells. Whether and to which degree it is moved upward out of a galaxy and what happens to this gas in the lower halo, is of crucial importance for the understanding of the chemical evolution of dwarf galaxies (e.g. Hensler & Rieschick 1999). In the work Mac Low & Ferrara (1999) for the first time a set of hydrodynamical simulations incorporating a relatively detailed model of the dwarf galaxy potential (including dark matter) was used and the simulations for a whole dwarf galaxy was run for more that 100 Myr. Still, the authors had to compromise e.g. by relatively basic treatment of the cooling processes and ignoring magnetic fields.

The hot gas inside the bubbles is predicted to be in the temperature range of 10^5 and 10^7 K (e.g. Weaver et al. 1977), which implies that the plasma will radiate in the extreme UV and soft X-ray regime. The ionized gas at the boundary layer between the hot interior and the cool shell wall should be visible in optical and UV emission lines, while the cool shell itself can be observed in 21cm emission. Since density of the substrate medium and especially the size of the energy depositing stellar association (from few O or even B stars to many thousands of OB stars as e.g. inside giant HII regions like 30 Dor or NGC 5471 in M101) span a large parameter space, the size of the bubbles can vary a lot, from pc to kpc scale (Chu 1995). The (more abundant) small bubbles do not break out of the disk of a galaxy. These bubbles do still structure the interstellar medium and should lead to ionized filaments, as observed in the Magellanic Clouds (e.g. Kennicutt et al. 1995) and the Milky Way (Haffner et al. 1999). They also lead to large regions of hot gas observed in the LMC (e.g. Chu & Mac Low 1990, Bomans et al. 1994) and the Milky Way (e.g. Snowden et al. 2000).

The observation of warm and hot gas in dwarf galaxies allows therefore to study the mechanism shaping the topology and phase structure of the ISM as well as the processes responsible for the chemical and (at least partly) the

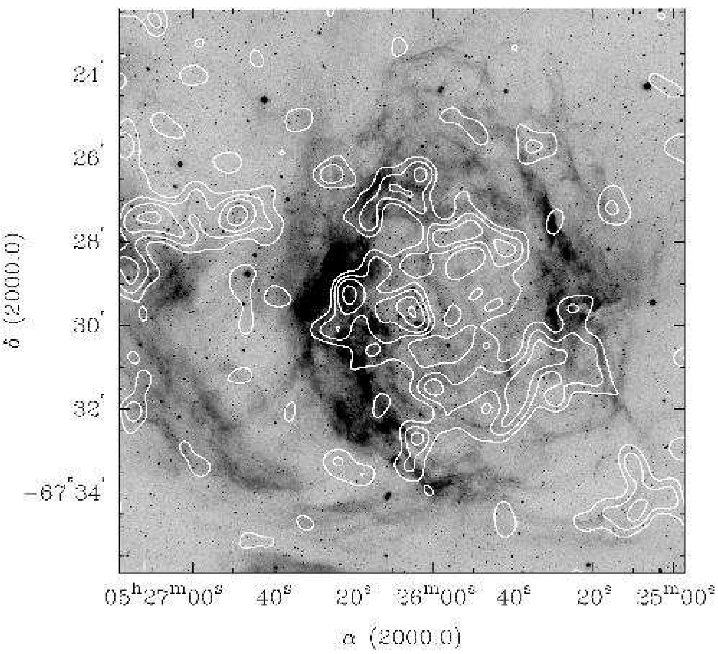

Figure 1: H_α image of the LMC superbubble N51D with contours of the ROSAT soft and medium band X-ray emission overplotted.

dynamical evolution of the host galaxy. Dwarf galaxies are supremely suited for this task. They present the most extreme environment for feedback of massive stars on the interstellar medium due to their shallow potential wells, their small sizes, and the absence of complicating other factors like density waves.

2 OB associations and the interstellar medium

Before going into details of the properties of diffuse X-ray emission of dwarf galaxies, it may be fruitful to check a few of the assumptions and theoretical predictions in smaller, better controlled, nearby systems, like the superbubbles in the Magellanic Clouds. Fig. 1 shows an H_α image of the superbubble N51D in the Large Magellanic Cloud (LMC). The structure is a fairly typical example of its class (Meaburn 1980). It shows a complete shell of ionized gas with a diameter of about 100 pc centered on one large OB association. Such a superbubble distinguishes itself physically from a ($\sim 1-50$ pc) bubble around a single star (Weis & Duschl 1999) and a kpc-sized supergiant shell (sometimes also called supershell) (Meaburn 1980; Chu 1995) around a large complex of OB associations.

N51D expands with a velocity of $\sim$ 35 km s^{-1}(Lasker 1980; de Boer &

Nash 1982) into the surrounding medium. Despite of some larger loop-like extensions of the H_α shell to the north and the south-west (as visible in Fig. 1), this superbubble appears to be still a closed volume. The difference in surface brightness between the eastern and western section is partly due a different density of the surrounding gas into which the superbubble expands. The gas is ionized by the OB association inside, which contains one the UV brightest stars in the LMC, the WC5+O8Iaf binary Sk-67 104 (= HD 36402). A detailed study of the OB association (Oey & Smedley 1998) yields an age of 3 Myr and determines from the observed stellar content the total energy input of the stars to the superbubble. N51D emits diffuse X-ray emission (Chu & Mac Low 1990) which is brighter near the eastern rim of the superbubble. Fig. 1 shows the H_α image of N51D overlayed with contours of the X-ray emission derived from an ROSAT PSPC archival data (Bomans et al. 2001a, in prep). While some X-ray emission inside N51D seems to stem from point sources (most probably X-ray binaries), diffuse emission is clearly present inside the cavity delineated by the H_α shell. The ROSAT data confirm the surface brightness enhancement at the bright, probably denser, eastern boundary of N51D first detected using EINSTEIN (Chu & Mac Low 1990), but also show considerable substructure here, not following one-to-one the H_α emission (Bomans et al. 2001a, in prep.). The temperature of the hot gas is about 5×10^6 K, when fitting spectra with collisional equilibrium models (e.g. Raymond & Smith 1977). The X-ray surface brightness and luminosity of N51D does not fit well to the predictions of the Weaver et al. (1977) model of an expanding superbubble and require an additional source of X-ray emission, which can be provided by supernova explosions of massive stars in the OB association, meaning inside the superbubble. As soon as the shock wave hits the dense shell wall, hot gas with high density and therefore surface brightness is produced, a process we may well observe right now at the eastern inner shell wall (Chu & Mac Low 1990, Bomans et al. 2001a, in prep.). It is interesting to note here, that the loop at the south-western edge of N51D is a separate diffuse X-ray region, which is tempting to be identified with a beginning outflow, similar to the one in the LMC superbubble N44 (Chu et al. 1993). With the availability of an HI synthesis map of the LMC (Kim et al. 1998), even some informations about the surrounding neutral gas density and topology can be derived. Therefore in the case of N51D all critical parameters for the evolutions of a bubble can be observationally determined or at least estimated.

The crucial determination of the metallicity of the diffuse hot gas is still missing. The current information on superbubbles does not give reliable metallicities or how metal-enriched and more metal-poor gas is distributed in the bubble and along the shell walls, much less than giving details on the actual mixing processes. ASCA observations of a sample of LMC supernova remnants prove at least the first assumption: the hot gas is indeed metal-enriched by the supernova explosion, but it shows also that mixing of hot metal-rich and cool metal-poor gas starts right away (Hughes et al. 1998).

3 Hot Diffuse Gas

3.1 Observations

The number of dwarf galaxies, which had their X-ray properties investigated is still relatively small. Of all galaxies observed with the EINSTEIN satellite (Giacconi et al. 1979) and compiled by Fabbiano et al. (1992), 8 dwarf galaxies are present (see Tab. 1). This list does not include the obvious cases of the LMC (e.g. Chu & Mac Low (1990), Wang et al. (1991)) and the SMC (Wang & Wu 1992). These two galaxies have small enough distances to study diffuse sources like supernova remnants or superbubbles individually. Only point sources were detected in the other dwarf galaxies of the Fabbiano et al. (1992) atlas with no convincing case of extended X-ray emission.

The sensitivity and spatial resolution improvement ROSAT (Trümper 1993) provided over EINSTEIN changed the conditions significantly, but still the number of observed and analyzed dwarf galaxies is still quite low, as demonstrated in Tab. 1. Here the relevant X-ray data of all dwarf galaxies with analysis of their X-ray emission are compiled. Due to its large luminosity, mass and clear disk structure, M 82 is not regarded as dwarfish galaxy and is therefore not included in this list.

An additional problem to interprete the X-ray emission of dwarf galaxies is the fact that both the EINSTEIN and the ROSAT samples are preselected to be galaxies which are for one or another reason interesting to the principal investigators of the original pointed observations or by chance inside the field of view. Therefore the samples are far from statistically well behaved. One attempt to avoid this problem has been undertaken by Schmidt et al. (1996). They used the ROSAT All Sky Survey (RASS) data and their catalog of nearby galaxies (radial velocity $< 500\,\mathrm{km\,s^{-1}}$) as input sample. Unfortunately the exposure time of the RASS is only a few 100 sec on average, yielding a quite low sensitivity.

The next step in X-ray observations of dwarf galaxies came with the ASCA satellite (Tanaka et al. 1994) which first employed CCD detectors in for X-ray astronomy, leading to a much higher spectral resolution (compared to the imaging proportional counters in EINSTEIN and ROSAT) combined with good sensitivity. Drawback of ASCA is its low spatial resolution of about $1.5'$, compared to about $25''$ for ROSAT PSPC or $5''$ for ROSAT HRI (detector without energy resolution). This low spatial resolution limits ASCA data effectively to be only an integrated spectrum of a dwarf galaxy without the possibility to distinguish between point sources and extended diffuse emission. The other problem of the ASCA data is the relatively hard band-path of 0.5 to 10 keV, versus 0.1 to 2.4 keV of ROSAT. This forces the combined analysis of ROSAT and ASCA datasets for analysis of relatively low temperature plasma. These limitations lead to only 2 dwarf galaxies analyzed with ASCA up to now, NGC 1569 (Della Ceca et al. 1996) and NGC 4449 (Della Ceca et al. 1997).

All objects emitting relatively soft (low energy) X-rays share an obser-

Table 1: X-ray detected dwarf galaxies

galaxy	D [Mpc]	M_B	point	diffuse	kT [keV]	references
LMC	0.05	-17.93	+	+	0.2-0.7	e.g. 1
SMC	0.07	-16.99	+	-?		e.g. 2
Scl dSph	0.08	-10.40	+	-		3
Car dSph	0.1	-11.60	+	-		3
For dSph	0.14	-12.60	+	-		4
IC 1613	0.7	-14.20	+	-?		5, 6, 7
IC 10	0.8	-15.20	+	-?		8, 9
NGC 6822	0.5	-14.70	+	○		5, 10, 11
Leo A	0.7	-11.30	-	○		11
NGC 205	0.8	-16.00	-	○		11
NGC 221	0.8	-15.80	+	○		12, 11
NGC 147	0.7	-14.80	-?	-		8, 13
NGC 185	0.6	-14.70	-?	-		8, 13
NGC 3109	1.2	-15.20	+	○		14
NGC 1569	1.4	-15.97	+	+	0.8	15, 16
Scl DIG	1.5	-10.42	+	○		17
NGC 625	1.5	-14.69	+?	+	0.2	18
Ho II	3.3	-16.67	+	-		19, 11
Ho IX	3.3	-13.52	+	-		20, 11
NGC 3077	3.3	-17.27	+	?		5
IC 2574	3.3	-17.26	+	+?	0.5	5, 21, 22
NGC 2366	3.3	-16.63	+	-		16, 9
KDG 061	3.3	-12.99	+?	-		13
UGC 6541	3.5	-13.42	+	-?		23
NGC 4449	3.5	-17.82	+	+	0.2, 0.8	5, 24, 25, 11
NGC 4214	3.5	-17.56	+	-?		9
NGC 4190	3.5	-13.85	+	○		5, 11
NGC 3738	3.5	-15.68	+?	-		13
NGC 5253	4.1	-17.70	+	+	0.3	5, 26, 23, 27
NGC 5408	4.1	-16.37	+?	-?	0.5	28, 21, 16, 11
UGC 6456	4.5	-13.49	+	+?		29, 13
He 2-10	5.7	-17.76	+	-?	0.5	21, 23, 30, 11, 31
NGC 1705	6.1	-16.34	-	+	0.2	32, 11
I Zw 18	7.9	-14.17	+	+		33, 34, 21, 16
NGC 4861	8.4	-16.62	+	+?	0.6?	5, 21, 23
NGC 1427A	15.2	-17.52	+?	+?	0.6?	35

(1) Snowden & Petre (1994), (2) Snowden (1999), (3) Zinnecker et al. (1994), (4) Gizis et al. (1993), (5) Fabbiano et al. (1992), (6) Eskridge (1995), (7) Lozinskaya et al. (1998), (8) Brandt et al. (1997), (9) Roberts & Warwick (2000), (10) Eskridge & White (1997), (11) Colbert & Mushotzky (1999), (12) Eskridge et al. (1996), (13) Lira et al. (2000), (14) Kahabka et al. (2000), (15) Heckman et al. (1995), (16) Stevens & Strickland (1998b), (17) Burstein et al. (1997), (18) Bomans & Grant (1998), (19) Zezas et al. (1999), (20) Miller (1995), (21) Fourniol et al. (1996), (22) Walter et al. (1998), (23) Stevens & Strickland (1998a), (24) Bomans et al. (1998), (25) Vogler & Pietsch (1998), (26) Martin & Kennicutt (1996), (27) Strickland et al. (1999), (28) Fabian & Ward (1993), (29) Papaderos et al. (1994), (30) Dickow et al. (1996), (31) Méndez et al. (1999), (32) Hensler et al. (1998), (33) Martin (1996), (34) Bomans (1999), (35) Hilker et al. (1997)

The distances and luminosities of the Local Group galaxies are taken from the compilation of Mateo (1998). For the other galaxies the data are taken from Schmidt et al. (1993) and the LEDA database, but all distances and M_B were recomputed relative to the HST based distance modulus of the Virgo cluster (Ferrarese et al. 1996). In column 3 and 4 a "+" denotes detection, "-" denotes non-detection, and "○" where no analysis of the data concerning this type of emission was performed or reported. An additional "?" denotes uncertain or contradicting evidence. Column 5 gives the temperature of the probable diffuse gas, when determined.

vational problem. The low energies are strongly absorbed by the galactic N_H, which implies, that studies of the soft diffuse emission is only possible in dwarf galaxies with sufficiently low foreground N_H. The imposes an additional strong and unavoidable selection bias on the X-ray properties of dwarf galaxies. For example, NGC 1569 does not show a very soft X-ray emission, while NGC 4449 does. The difference may be intrinsic to the galaxies, but since the foreground N_H of NGC 1569 is much higher, it is equally possible that all soft X-ray emission of NGC 1569 is just absorbed.

3.2 Diffuse gas and outflows

As we saw in section 2, the natural results of some locally increased star formation rate is a superbubble, which expands in the neutral interstellar medium of the host galaxy. The evolution of the superbubble inside a dwarf galaxy is different since the conditions are different from that in a spiral galaxy. Due to the small size of the dwarf galaxy, a big association takes up a significant part of the host galaxy. Additionally dwarf galaxies tend to have larger OB associations than spiral galaxies when scaled to the galaxy sizes (Elmegreen et al. 1994). The bubble, which has to develop will not be sheared in the solid-body rotation field of the dwarf galaxy and expands undisturbed to larger size due to the thicker HI layer (e.g. Skillman 1995). As soon the shell starts to break out, the shallow gravitational potential well of the dwarf galaxy makes it more likely for the bubble to reach large distances from the host galaxy. The low metallicity inhibits cooling which helps maintain a high

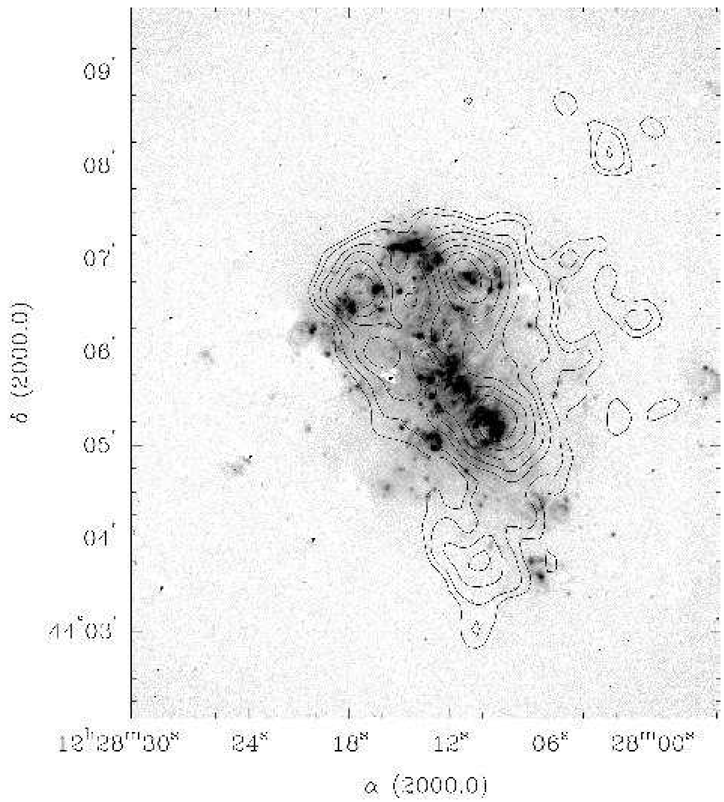

Figure 2: Pure H_α image of the irregular galaxy NGC 4449 with contours of the ROSAT soft and medium band X-ray emission overplotted.

pressure in the bubble (before breakout).

The catch in this scenario is the extended dark matter halo of dwarf galaxies. If the maximum disk interpretation of rotation curves of dwarf galaxies is correct (Swaters 1999), dwarf galaxies are even more dark matter dominated than disk galaxies. This implies, that we need some assumptions on shape and total size of the dark matter halo to estimate if vented out gas will stay in the gravitational potential or will be lost into the intergalactic medium. Due to the large dark matter fraction of dwarf galaxies this correction is much more critical than in disk galaxies.

Even in the small current sample (Tab. 1) at least 6 larger and smaller dwarf galaxies show exactly what this picture implies: strong star formation and large H_α shells and filaments sticking out into the lower halo. Good examples are NGC 4449 (Bomans et al. 1997; Vogler & Pietsch 1997) and NGC 1569 (Heckman et al. 1995). Indeed, diffuse X-ray emission can be found inside some of the shells as demonstrated for NGC 4449 in Fig. 2, but the integration times used for the PSPC observations turned out to be to

small for for deriving useful spectra for determining the plasma conditions. Especially, the data are not of sufficient quality to allow the critical test if the hot gas is metal enriched compared to the global interstellar medium in these galaxies.

The most favorable object for the metallicity test is I Zw 18, the most metal poor galaxy known (e.g. Skillman & Kennicutt 1993). Because of the low metallicity of about 1/50 solar, any enrichment of the hot gas would make a big difference in the plasma emissivity. Unfortunately, the ROSAT spectrum (Martin 1996) is again not good enough to determine the metallicity of the hot gas to reasonable degree of certainty (Bomans 1999).

Two other problems are apparent when analyzing the diffuse X-ray emission of dwarf galaxies: Due to their small intrinsic size, even at moderate distances the galaxies represent only a few resolution elements of the ROSAT PSPC or even worse the ASCA SIS. This makes contamination from points sources a real concern (e.g. Vogler & Pietsch 1997). The ROSAT HRI with its about 5 times better spatial resolution (but without spectral resolution) had a much higher background, making it a much inferior instrument for the detection of the low surface brightness diffuse emission. Still, with long exposures, the point source content of the PSPC images can be checked and the brighter diffuse emission be studied (Bomans 1998, Strickland et al. 1999). Fig. 3 shows a deep ROSAT HRI image of I Zw 18 as contours overlayed over an HST H_α image.

The other problem is the plasma itself. If it expands rapidly into the lower density halo, the gas cools adiabatically, but roughly maintains its ionization patter, recombination lacks behind cooling (Breitschwerdt & Schmutzler 1999). Therefore the standard analysis of X-ray spectrum using the coronal equilibrium plasma codes (Raymond & Smith 1977; Mewe et al. 1995) does not necessarily determine the physical parameters correctly, even if one has a very good spectrum. Much higher spectral resolution together with good signal to noise ratio is needed in the spectra to check for the presence and size of the effect and finally account for non-equilibrium conditions in the derived plasma properties. While the spectral resolution of ASCA helps, it could not produce sufficiently high quality spectra of the diffuse gas (della Ceca et al. 1997, 1998).

3.3 Diffuse hot halos

With outflows of hot gas out of dwarf galaxies observed in at least 6 dwarf galaxies with strong star formation (Tab. 1), the question arises what the ultimate fate of this gas will be. This problem is firmly linked to the understanding of chemical evolution of dwarf galaxies due to the metal-enriched nature of the hot gas. Current theories of chemical evolution of dwarf galaxies postulate the presence of galactic winds to account for both the star formation history and the current (low) metallicities of dwarf galaxies (e.g. Matteuchi & Chiosi 1983; Hensler & Burkert 1990). Also the best explanation for the very homogeneous metallicity level of practically all dwarf galaxies (Kobulnicky &

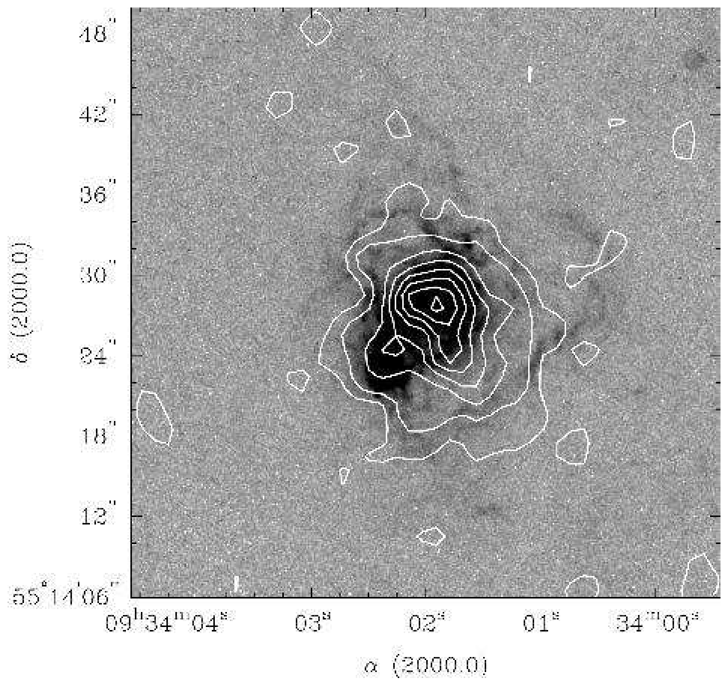

Figure 3: Continuum subtracted HST WFPC2 H_α image of the dwarf galaxy I Zw 18 with contours of X-ray emission from ROSAT HRI overplotted.

Skillman 1996; 1997) seems to be outflows of hot metal enriched gas, which stays in the halo for a while and then drizzles down to the galaxy again (e.g. Pantelaki & Clayton 1987; Roy & Kunth 1995; Tenorio-Tagle 1996). For more arguments in favor and against this picture see Skillman (1997).

A hot gaseous halo around a dwarf galaxy should be expected, either from a galactic wind (where most of the mass really leaves the potential well of the dwarf galaxy into the intergalactic space) or from outflows (which pump material in the halo but with velocities below escape velocity of the potential well of the dwarf galaxy). How this halo would look like is highly depending on the properties of the gravitational potential and the history of star formation both in the temporal and spatial domains. It is also depending on the metallicity, density, and topology of the gas itself due to the cooling processes. In any case, hot, low metallicity, low density gas cools slowly (e.g. Boehringer & Hensler 1989). One more specific hint can be extracted from the simulations of Mac Low & Ferrara (1999) which showed that in a relatively realistic gravitational potential the hot gas (and therefore the metals) can reach large distances from the host galaxy. They also showed that the structure may be more like pockets of hot gas and less a smooth hot halo. This last conclusion should be less dependable, since the cooling of the hot gas is critical here and had to be treated in a relatively simplistic manner

in these simulations. No other set of simulations is available in the literature yet, which follows the evolution of bubbles and outflows long enough to study the properties and the ultimate fate of the hot gas in dwarf galaxies. Still, one can use the results on hot halos of low velocity dispersion elliptical galaxies to make rough predictions. Adiabatic compression would keep the halo gas hot and the calculations predict temperatures in the order of 0.2 keV for galaxies with masses similar to the LMC and below (e.g. Nulsen et al. 1984).

On the observational side, two attempts have been made to look for such extended hot halos around dwarf galaxies. The first program used pointed PSPC observations of 3 irregular galaxies with distances in the order of 10 Mpc (Bothun et al. 1994). In the two exposures which reach decent sensitivity the target galaxies where detected, but only as sources with hard spectrum and without spatial extension. The sensitivity of the observations results in a non-detection of soft ($\sim$ 0.2 keV) extended halo with masses of 10^9 $M_\odot$ or above. The other search for hot extended halos around dwarf galaxies uses the ROSAT archive to select all star forming dwarf galaxies within a distance of 6 Mpc which had PSPC observations (pointed and serendipitous) and low foreground N_H column density. The sample contained 49 galaxies with PSPC data, but no large hot halo was detected in the first pass of data analysis (Bomans 1998). The detectable mass of hot gas in a spherical hot halo with 10 kpc radius around a galaxy at 6 Mpc distance is about 10^6 $M_\odot$ in a typical 10 ksec exposure. The survey detected diffuse hot gas in several dwarf galaxies, but it is always located quite close to the galaxies (in order of 2 kpc), and is linked to large H_α shell structures.

If the basic assumptions are right, then three conclusions can be drawn: 1) The hot gas expands to very large distances (or is lost to the intergalactic space) giving it such low surface brightness that the present ROSAT PSPC data are not sensitive enough to detect it. 2) The gas is highly clumped as implied by Mac Low & Ferrara (1999) and not a smooth halo. Such hot gas pockets would be missed by the analysis methods tailored to detect extended diffuse emission. 3) The gas could be at such low temperature that the peak of the spectrum is located outside the ROSAT energy range. The stringent limits for the EUV flux of large star forming galaxies using the ROSAT WFC (Read & Ponman 1995) make at least the third possibility quite unlikely.

An alternative way to search for hot plasma in the halos of nearby dwarf galaxies was tested by Bowen et al. (1997). They used HST high-dispersion UV spectra to 3 QSO in the background of the dwarf spheroidal galaxy Leo I. No highly ionized gas was detected, again hinting that the possibly missing hot halos are not at temperatures of a few 10^5 K, as traced by the CIV UV lines.

3.4 Integral spectra

Up to now, only for two dwarf galaxies X-ray spectra of higher spectral resolution (the CCD detectors of ASCA): NGC 1569 (Della Ceca et al. 1996) and NGC 4449 (Della Ceca et al. 1997) have been analyzed. In both cases

the signal to noise ratio is not good enough to measure reliable metallicities of the gas using lines/line complexes. Still, the much larger spectral range allowed a look at the higher energy part of the integrated X-ray spectrum of the two dwarf galaxies. The spectra showed in both cases the need for at least 2 components, a soft one with kT $\sim$ 0.8 keV and a hard component with kT $\sim$ 3.5 keV. In the case of NGC 4449 an additional very soft component (kT $\sim$ 0.2 keV) is needed, too, consistent with the ROSAT-only analyzes of Bomans et al. (1997) and Vogler & Pietsch (1997). The hard component is best interpreted as a mix of young supernova remnants and X-ray binaries, while the soft and especially the very soft components is largely due to diffuse hot gas, consistent with the extended nature of the emission on the ROSAT images. It is worth to note, that the ASCA spectra of both observed galaxies could only be detected out to $\sim$ 6 keV, making such dwarf galaxies only weak contributors to the hard X-ray background (della Ceca et al. 1996).

4 Diffuse warm gas

Structure, occurrence, and ionization of the diffuse warm gas and especially the presence of large ionized shells in dwarf galaxies were discussed in a number of recent publications (e.g. Martin 1997, 1998; Hunter & Gallagher 1997; Hunter et al. 1993). Here I will concentrate mostly on the dynamics of the ionized gas and its implications for the fate for the hot gas.

First it is important to note here, that the warm ionized gas cannot be used for the metallicity determination of the outflows. We have seen that there are signs of at least some mixing at the boundary layers between hot and cold gas and therefore a metal enrichment of warm gas. This makes the observation of the optical emissions lines of the shells and outflows tempting as alternative way to estimate the metal content of the outflows. Still the spectra cannot be treated with the usual methods as used for normal HII region. The line ratios clearly indicate a complex interplay of normal stellar photoionization, photoionization by a diffuse photon field, shock ionization, photoionization by X-ray, and even turbulent mixing layers (Hunter & Gallagher 1997; Martin 1998, Tüllmann & Dettmar 2000). With insufficient information to even determine the ionization mechanism(s), a direct derivation of ionic abundances from optical emission lines for the diffuse ionized gas is out of the question (at least for now). A helpful alternative method may be the use of interstellar UV absorption lines to background QSOs. Unfortunately, no usable chance alignment of a dwarf galaxy outflow with a sufficiently bright background source has been found.

When one finds a dwarf galaxy showing large H_α shells, which extend to a size larger than the stellar body of the dwarf galaxy, the first critical question is if this ionized gas is really expanding away from the dwarf galaxy. Observationally the dynamics of the ionized gas can be studied either with high-dispersion, long-slit spectroscopy, or using a Fabry-Perot interferometer. While the long-slit approach only uses one spatial axis, it is stable against

changes in instrumental and weather conditions, relatively easy to reduce, and can provide high spatial and spectral resolution (~ 10 km s^{-1}). The one-dimensional spatial axis allows also a very good sky subtraction and therefore sensitivity to faint features. Producing a 2-d map on the other hand, requires offsetting the slit and is therefore very telescope time intensive. The scanning Fabry-Perot approach delivers a real data cube with two spatial and a spectral axis, but is somewhat susceptive to changes in the observing conditions and the data relatively hard to handle. Unfortunately, no Fabry-Perot dataset on dwarf galaxies has delivered yet at the same time the high spectral resolution and sensitivity of the best long-slit data. The alternative use of the Fabry-Perot as spectrometer delivers very high sensitivity at the cost of low spatial resolution and is therefore of only limited use for the study of outflows.

As an example I present here an analysis of the galaxy NGC 1705. NGC 1705 contains several large H_α shells (Meurer et al. 1992), two of which show up in a deep ROSAT PSPC pointing as very soft, diffuse X-ray sources (Hensler et al. 1998). The data presented here were taken with the ESO VLT and the ESO NTT and are going to be discussed in detail in Bomans et al. (2001b, in prep.). In Fig. 4 the continuum subtracted H_α image of NGC 1705 is shown with contours of the Gunn-r continuum image overlayed. The body of the galaxy is relatively smooth, indicating a long phase of low star formation activity, and one bright knot, which harbors a young globular cluster (Melnick et al. 1985; Ho & Filippenko 1996). The about 1.8 kpc large stellar body (Holmberg diameter) of the galaxy is nearly filled with HII regions and large ionized shells and filaments extend radially out to more than 2.5 kpc from the center of the dwarf galaxy. The structure appears roughly bipolar, consistent with hydrodynamical simulations, but shows a very complex substructure with interlocking and overlapping individual shells and filaments. One should keep in mind that we see in the image a 2-d projection of the 3-d structure, which may explain at least some of the shells-inside-shells as line-of-sight projection. The currently available HI synthesis map is of to low spatial resolution to study the detailed dynamic of the gas, but shows that NGC 1705 is embedded in a large HI envelope.

Fig. 5 shows a long-slit spectrum taken with a position angle of 310 deg, roughly aligned to the central star cluster of NGC 1705 and the bright foreground star in the north-west. The spectrogram runs top to bottom from north-west to south-east and shows a spectral range of 60Å centered on the H_α line and the two [NII] lines. Note that the lines are redshifted due to the radial velocity of NGC 1705 and the [NII] lines quite weak due to the subsolar metallicity of NGC 1705. Just below the bright star (the residuum from continuum subtraction running as white line left to right near the top the the spectrogram) the H_α line splits into two components and merges again at the beginning of the stellar body. This Doppler ellipse is the sign of an expanding bubble and coincides exactly with the bright loop in the north-west. The expansion velocity is 75 km s^{-1}. The H_α line maintains a complex structure over the whole stellar body of NGC 1705, not surprisingly given the complicated structure of the H_α emission in this region visible in Fig. 4. At the bottom of

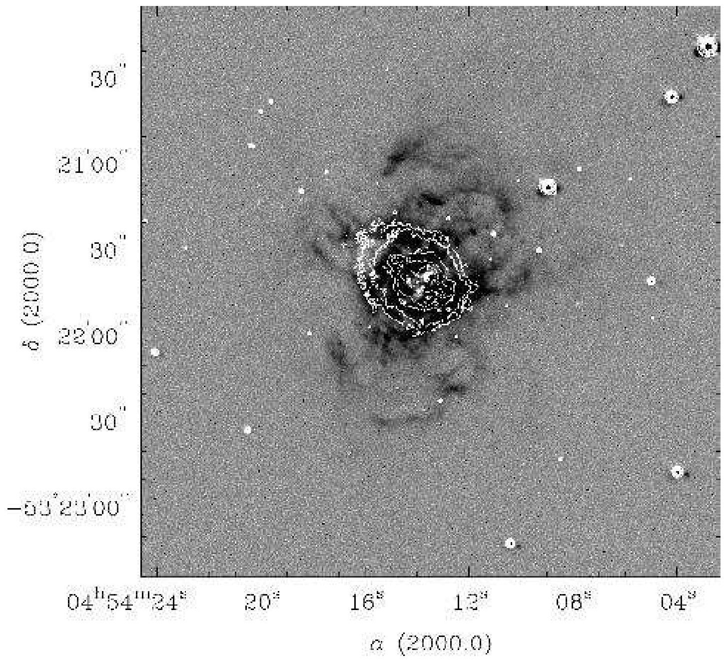

Figure 4: Continuum corrected VLT H_α image of NGC 1705 with contours of the continuum emission overplotted.

the spectrogram the H_α line does not show a line split, but the width of the line is large, implying motions with velocities below the spectral resolution of $\sim 30\ \mathrm{km\,s^{-1}}$. Interestingly, the slit cuts through another large shell, which is, contrary to the shells in the north-west, not detected in the deep ROSAT image. It is tempting to make a link between the lower expansion velocity of the shell in the south-east and the missing X-ray emission. Similar velocities are seen also in an spectrum with a position angle of 230 deg (Marlowe et al. 1995).

Still, the situation is a bit more complicated, since neither the $75\ \mathrm{km\,s^{-1}}$ nor the $30\ \mathrm{km\,s^{-1}}$ shock speed would give rise to X-ray emission. It requires about $200\ \mathrm{km\,s^{-1}}$ to get post-shock temperatures above 10^6 K (McKee 1987). Simple projection effects are not likely to make a large effect for expanding bubbles. The probable explanation comes from the inherent selection effect of using the warm ionized gas as tracer of the flow: the gas detected with the spectrometer is the gas with highest surface brightness and therefore density, which is the least probable to show the highest velocities. We apparently measure the large scale expansion of the superbubble driven by the overpressure of the hot gas inside, which is heated by the supernovae. As we have seen in the case of N51D, a significant part of the X-ray emission results from recent supernovae shocks hitting the shell walls. Therefore there is a link between the temperature of the hot gas and the expansion velocity, but it is

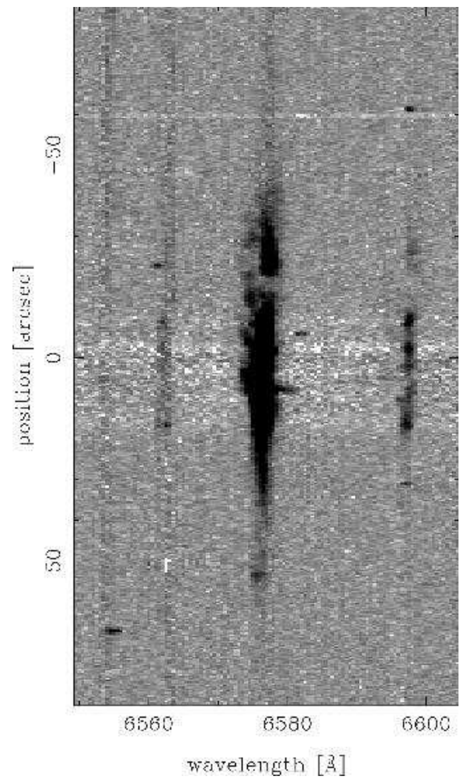

Figure 5: High-dispersion spectrogram of one slit position through NGC 1705.

not the simple post-shock temperature from the large-scale shock, hitting the surrounding interstellar medium, but local heating near the inner shell wall. Indeed, we detect hot gas inside the shell walls not outside (Bomans et al. 2001b, in prep.).

This is also consistent with the missing correlation of the X-ray temperature with global galaxy parameters (Tab. 1). The visible clustering of the X-ray temperature of the diffuse gas near 0.2 and 0.8 keV could be an effect of the location of the local minima visible in the cooling curve (Boehringer & Hensler 1989) at low metallicity.

The shells of NGC 1705 are clearly expanding out of the galaxy and they are (at least in part) filled with hot gas. The question is now, what will be the fate of this bubbles? The faintest shells and filaments visible on our VLT H_α image reach the rim of the HI envelope of NGC 1705. If they are still expanding at this radius, they are likely going to speed up when hitting the gas density gradient. Unfortunately, the filaments are very faint and it is hard to measure their radial velocity. Even with a measured velocity, the lack of HI also means that the rotation curve and therefore the potential of the galaxy is not well constrained there. These problems are generic to the analysis method

and should be kept in mind when evaluating similar analyzes of the mass loss from dwarf galaxies (e.g. Martin 1998).

There is another effect, which may be important for the processes discussed here. Ordered magnetic fields, if present, could have a large influence on the conditions of the outflows and the kinematics of the warm and hot gas. Unfortunately, the knowledge about magnetic fields in dwarf galaxies is very sparce. From theoretical considerations no large-scale ordered magnetic fields are to be expected in dwarf galaxies, but at least the LMC (Klein et al. 1993) and NGC 4449 (Chyży et al. 2000) do show such magnetic fields. Still, both galaxies are at the upper mass and luminosity boundary for dwarf galaxies and the conditions in lower mass dwarf galaxies are unexplored yet.

5 Conclusions and Outlook

The link between superbubbles in the interstellar medium and diffuse X-ray emission has been clearly demonstrated (e.g. Chu & Mac Low 1990) and even some larger bubbles have been shown to be filled with hot gas (e.g. Wang et al. 1991, Bomans et al. 1994). The detailed physics of such bubbles is still ill observed. We do not know the metallicity of the hot gas, the ionization condition (equilibrium or non-equilibrium), the details of the interaction between hot gas and cool shell, or the presence and properties of cold cloudlets inside the hot cavity. In dwarf galaxies, the presence of extended hot gas could be proven and even that parts of this gas is located far away from its possible sites of creation (e.g. Heckman et al. 1995, Bomans et al. 1997). The number of such studies is still very small (see Tab. 1) and limited to galaxies with recent strong star formation. No dwarf galaxy with diffuse hot halo is known up to now. Likewise no dwarf galaxy with extended X-ray emission but currently low star formation rate has been found up to now. Clearly we do not know from observation, what the fate of the hot gas will be. Using the kinematics of the warm ionized gas together with the HI rotation curve one can estimate if hot gas inside a bubble will escape the potential well of a dwarf galaxy (e.g. Martin 1998), but the uncertainties are large, partly due to the big uncertainties in determining the dark matter potential (e.g. Swaters 1999), partly due to the current inability to measure the velocity of the faintest shells and the warm ionized gas with highest velocities (see Section 4).

The determination of the physical parameters of the hot gas are hampered by the quality of the X-ray spectra and the contamination with point sources. The new X-ray telescopes (XMM-NEWTON and CHANDRA) are now in orbit and are working well. Especially XMM-NEWTON promises large improvements in the quality of the spectra due to its unmatched sensitivity and good spatial resolution of $\sim 15''$. CHANDRA is especially well suited for the study of the point source population due to its very good spatial resolution of $\sim 0.5''$, but lower sensitivity. Unfortunately, most of the diffuse X-ray emission is expected to be in the very soft X-ray regime (see Tab. 1), where

both satellites are hard to calibrate. Still, at least for the dwarf galaxies with brighter diffuse X-rays the new instruments should allow to analyze the plasma conditions and measure metallicity of the hot gas. This will provide a big step forward in testing the current dwarf galaxy evolution scenarios.

For the diffuse warm gas, the near futures looks also promising, with several 8-10m class telescopes currently coming online. This will enable us to study the kinematics of the outflows even at low surface brightness, hunt for very high velocity gas and presumably extremely faint outer halo gas using emission lines and quasar absorption lines. These methods should also help to better determine the mass distribution and total mass of dwarf galaxies, leading to improved estimates on the escape fraction of the hot gas and therefore the metals.

While we started to answer the question if diffuse warm and especially hot gas is a common constituent of the interstellar matter in dwarf galaxies, the detailed physics of its creation, and evolution, as well as the links to global evolution of dwarf galaxies and the intergalactic medium have only slightly been touched yet. There should be exiting years to come!

Acknowledgments

The author is very grateful to K. Weis for critically and thoroughly reading the manuscript and many stimulating discussions. Furthermore, the author likes to thank Y.-H. Chu, M. Dahlem, K. Dennerl, R.-J. Dettmar, W.J. Duschl, G. Hensler, U. Hopp, N. Junkes, M.-M. Mac Low, P. Papaderos, G. Richter, E.D. Skillman, R. Tüllmann, M. Vogler, and M. Urbanik for discussions on many facets of dwarf galaxies and outflows. This work was supported by Verbundforschung grant 50 OR 99064 and the Bonn-Bochum Graduiertenkolleg "Magellanic Clouds and other Dwarf Galaxies". This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This work has also made use of the NASA's Astrophysics Data System Abstract Service and the LEDA database (http://leda.univ-lyon1.fr).

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